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Stray-light correction algorithm for spectrographs

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Abstract
In this paper, we describe an algorithm to correct a spectrograph's response for stray light. Two recursion relations are developed: one to correct the system response when measuring broad-band calibration sources, and a second to correct the response when measuring sources of unknown radiance. The algorithm requires a detailed understanding of the effect of stray light in the spectrograph on the instrument's response. Using tunable laser sources, a dual spectrograph instrument designed to measure the up-welling radiance in the ocean was characterized for stray light. A stray-light correction algorithm was developed, based on the results of these measurements. The instrument's response was corrected for stray light, and the effects on measured up-welling in-water radiance were evaluated.

1. Introduction

Spectrographs are dispersive instruments with multi-element detectors that enable simultaneous acquisition of an entire spectrum over some finite spectral width. With the rapid improvements in detector-array technologies, spectrographs are now being used in a variety of commercial and scientific applications. There are intrinsic limitations in the background signal originating from radiation scattered from imperfections in the grating and other optical elements. This unwanted background radiation, called stray light, while small—of the order of 0.01% or less of the incident spectral radiance in a single grating spectrograph—can give rise to unforeseen errors, often much larger than anticipated, when the spectral distribution of a source being measured differs significantly from the spectral distribution of the calibration source. This is a situation routinely encountered in oceanographic measurements, for example, where instruments are calibrated against incandescent sources with a peak radiance in the short-wave infrared and subsequently used to measure the radiance of the ocean, which peaks in the blue spectral region.

In this paper, we describe a recursion relation to correct a spectrograph's responsivity and an unknown source's radiance for effects of stray light. Using tunable, narrow-band laser sources available on the newly developed facility for Spectral Irradiance and Radiance responsivity Calibrations using Uniform Sources (SIRCUS) at the National Institute of Standards and Technology [1], a spectrograph can be fully characterized for stray light, and model parameters for the stray-light correction algorithm can be developed [2]. As an example, results from the characterization and stray-light correction of a dual CCD spectrograph, the Marine Optical System (MOS), are presented.

2. Stray-light correction algorithm

In general, the total signal from element i of a CCD or diode array spectrograph is given by the equation:

$$S_i = \int r_i(\lambda) L(\lambda)\, \mathrm{d}\lambda, \qquad (1)$$

where $r_i(\lambda)$ is the spectral responsivity of element i and $L(\lambda)$ is the spectral radiance of the source being measured. Note that $r_i(\lambda)$ is the spectral responsivity of element i when considered as part of the spectrograph and includes effects such as grating efficiency and mirror losses. For monochromatic radiation, the entrance slit is spatially imaged on the detector. The image

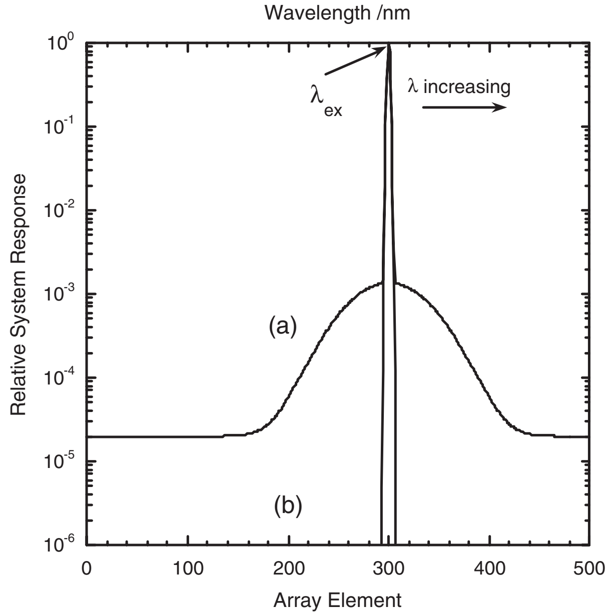

Figure 1. (a) Observed and (b) idealized relative response of a spectrograph to a monochromatic excitation source at wavelength λ_{ex}.

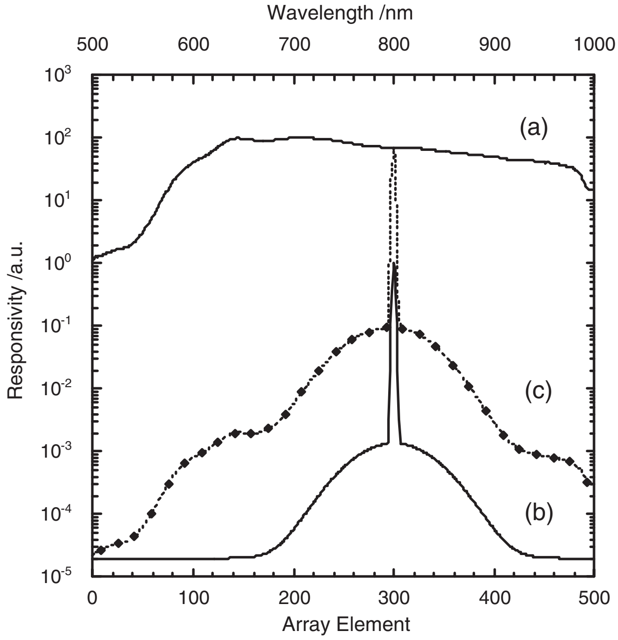

Figure 2. (a) Spectrograph's absolute spectral responsivity, $\bar{r}(\lambda)$. (b) Slit scatter function for element 300, $\sigma_{300}(\lambda_{300} - \lambda)$. (c) Absolute spectral responsivity of element 300.

is modified by scattered light within the spectrograph and every element in the array can therefore have a finite response to this monochromatic radiation, as shown in figure 1. As the wavelength changes, the spatial image moves across the array. There is a fixed relationship between the excitation wavelength and the array element that the image is centred on. Expressed as a function of wavelength rather than array element, this normalized spatial image function is known as the instrument's slit scatter function $\sigma_i(\lambda_i - \lambda)$ [3], with the exit slit determined by the element's spatial width. λ_i corresponds to the wavelength of element i's maximum responsivity.

Knowing this relationship enables us to determine the fraction of incident light at some wavelength that is scattered onto a particular element. For example, for the wavelength λ_{ex} in figure 1, 0.002% of the light that would be imaged on element 300 in an idealized system is actually scattered onto element 100. Assuming each element in the detector array has the same average spectral responsivity, the responsivity of element 100 to radiation at wavelength λ_{ex} is 0.002% of the responsivity of element 300.

Following Kostkowski [3], the total responsivity of element i can be approximated by the convolution of the slit scattering function and the maximum responsivity of each array element $\bar{r}(\lambda)$ (figure 2):

$$r_i(\lambda) = \bar{r}(\lambda)\sigma_i(\lambda_i - \lambda). \tag{2}$$

Further, separating equation (1) into an in-band (ib) and an out-of-band (oob) component and assuming that the source radiance is approximately constant over the in-band spectral width, equation (1) can be written as:

$$\begin{aligned} S_i &= \int_{\mathrm{ib}} r_i(\lambda)L(\lambda)\,\mathrm{d}\lambda + \int_{\mathrm{oob}} r_i(\lambda)L(\lambda)\,\mathrm{d}\lambda, \\ S_i &= L(\lambda_i)R_i(\lambda_i) + \int_{\mathrm{oob}} \bar{r}(\lambda)\sigma_i\,(\lambda_i - \lambda)\,L(\lambda)\,\mathrm{d}\lambda, \end{aligned} \tag{3}$$

where λ_i is the wavelength corresponding to the peak responsivity of element i, $L(\lambda_i)$ is the source radiance at λ_i, and $R_i(\lambda_i)$ is the integrated in-band responsivity of element i:

$$R_i(\lambda_i) = r_i(\lambda_i)\int_{\mathrm{ib}} \sigma_i(\lambda_i - \lambda)\,\mathrm{d}\lambda. \tag{4}$$

Measuring a calibration source of known spectral radiance, $L_{\mathrm{c}}(\lambda)$, and solving for $R_i(\lambda_i)$ in equation (3), the integrated in-band responsivity of pixel i can be written:

$$R_i(\lambda_i) = \frac{S_i}{L_{\mathrm{c}}(\lambda_i)} - \frac{1}{L_{\mathrm{c}}(\lambda_i)}\int_{\mathrm{oob}} \bar{r}(\lambda)\sigma_i(\lambda_i - \lambda)L_{\mathrm{c}}(\lambda)\,\mathrm{d}\lambda. \tag{5}$$

The second term on the right-hand side of equation (5) is the stray-light contribution to the total responsivity. Utilizing the inherently discrete nature of the spectrograph detector array and substituting equation (4) for $\bar{r}(\lambda)$, a recursion relation is developed for $R_i(\lambda_i)$:

$$\begin{aligned} R_i^{(n)}(\lambda_i) &= \frac{S_i}{L_{\mathrm{c}}(\lambda_i)} - \frac{1}{L_{\mathrm{c}}(\lambda_i)\int_{\mathrm{ib}}\sigma_i(\lambda_i - \lambda)\,\mathrm{d}\lambda} \\ &\quad \times \sum_{\mathrm{oob}} R_j^{(n-1)}(\lambda_j)\sigma_i(\lambda_i - \lambda_j)L_{\mathrm{c}}(\lambda_j)\Delta\lambda, \end{aligned} \tag{6}$$

where $\Delta\lambda$ is the pixel-to-pixel wavelength spacing and j extends over all elements of the array (i.e. 512 elements in the example considered). The original input values to the responsivity are the signals divided by the radiance of the calibration source:

$$R_i^{(0)}(\lambda_i) = \frac{S_i}{L_{\mathrm{c}}(\lambda_i)}. \tag{7}$$

It is straightforward to extend the above discussion to correct the radiance of a source with an unknown spectral distribution. In this case, the recursion relation is given by the expression:

$$L^{(n)}(\lambda_i) = \frac{S_i}{R_i(\lambda_i)} - \frac{1}{R_i(\lambda_i)\int_{\mathrm{ib}} \sigma_i(\lambda_i - \lambda)\,\mathrm{d}\lambda} \times \sum_{\mathrm{oob}} R_j(\lambda_j)\sigma_i(\lambda_i - \lambda_j)L^{(n-1)}(\lambda_j)\Delta\lambda, \quad (8)$$

where

$$L^{(0)}(\lambda_i) = \frac{S_i}{R_i(\lambda_i)}. \quad (9)$$

3. Example: the MOS

The MOS is a dual-spectrograph instrument developed for in-water measurements of down-welling solar irradiance and up-welling radiance [2, 4]. The MOS system contains two single-grating spectrographs, one to measure light in the near-ultraviolet and visible from 340 nm to 640 nm (the blue spectrograph), and one to measure light in the red and near-infrared from 550 nm to 955 nm (the red spectrograph) [4]. A dichroic beamsplitter separates the input radiance, reflecting the blue and green portion into the blue spectrograph and transmitting the red and near-infrared portion into the red spectrograph. Each spectrograph utilizes a 512 × 512 element CCD array to detect incident radiation. When acquiring an image, the signals from the central 384 pixels in each column are averaged.

The MOS Profiler [5] was characterized using broadly tunable, narrow-band lasers on SIRCUS [2]. In figure 3, the red spectrograph's slit scatter function is shown for 765.3 nm excitation, the wavelength giving the maximum responsivity for element 276. Finely tuning the lasers enabled the in-band area to be measured for element 276, as shown in the inset to figure 3. The correction algorithm was complicated by the presence of a second-order diffraction peak incident onto the CCD array. Spectral measurements were required to fully characterize the out-of-band response and include the reflection peak in the slit scatter function of each column i.

Using the characterization results from the SIRCUS measurements, a stray-light correction algorithm was developed and was applied to MOS Profiler system responses and test data sets from the Marine Optical Characterization Experiment 5 (MOCE-5) cruise [6]. The MOS Profiler was calibrated against a lamp-illuminated integrating sphere of known spectral radiance and the responsivity was corrected using equation (6). The uncorrected and corrected responsivities are shown in figure 4. The responsivity of both spectrographs converged to a stable (constant) solution after four iterations of equation (6), changing less than 0.1% over the next six iterations. There was a stray-light correction to the responsivity of approximately 10% for the red spectrograph and 5% for the blue spectrograph. The correction increased dramatically in the blue spectrograph below 400 nm and for both spectrographs in their overlap region (figure 4). The stray-light-corrected integrated in-band responsivity calibration agreed with the SIRCUS measurements to within approximately 2% with the exception of the 550 nm to 580 nm spectral region for the red spectrograph and the 350 nm to 380 nm spectral region for the blue spectrograph. These are regions of low responsivity with 50% of the signal or more coming from stray light. We estimate the uncertainty in the algorithm to be approximately 10%. The divergence between the SIRCUS measurements and the stray-light-corrected broad-band source measurements reflects the uncertainty in the model.

Finally, in-water up-welling radiance measurements taken with the MOS Profiler during the MOCE-5 cruise were corrected for stray light using equation (8). In figure 5, we show corrected and uncorrected up-welling radiance measurements from Station 13. Note the dramatic improvement in the measured up-welling radiance between the two spectrographs in their overlap region. The magnitude of the correction varies spectrally in each spectrograph and is a function of the spectral distribution of the measured up-welling radiance, as expected.

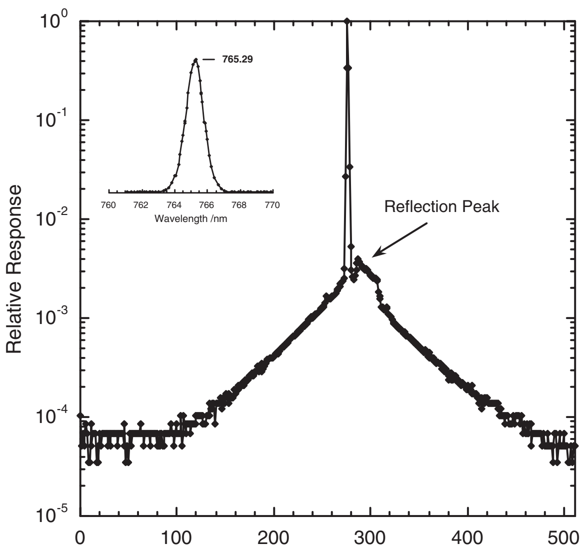

Figure 3. The MOS Profiler red spectrograph slit scatter function for element 276. Inset: the in-band spectral responsivity of element 276.

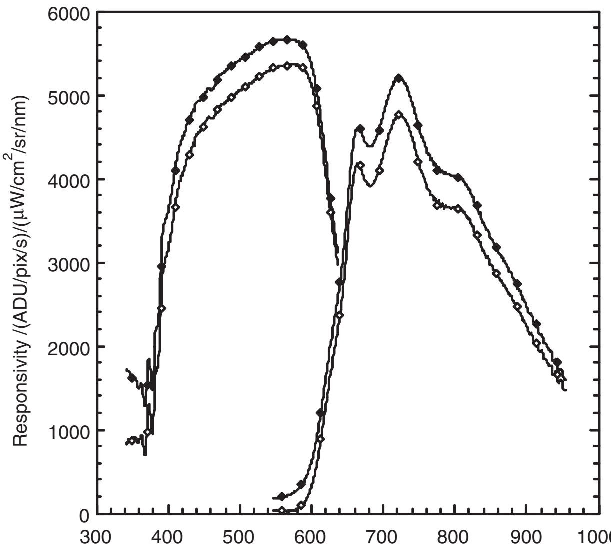

Figure 4. The uncorrected (♦) and stray-light-corrected (◊) responsivity of the MOS Profiler red and blue spectrographs.

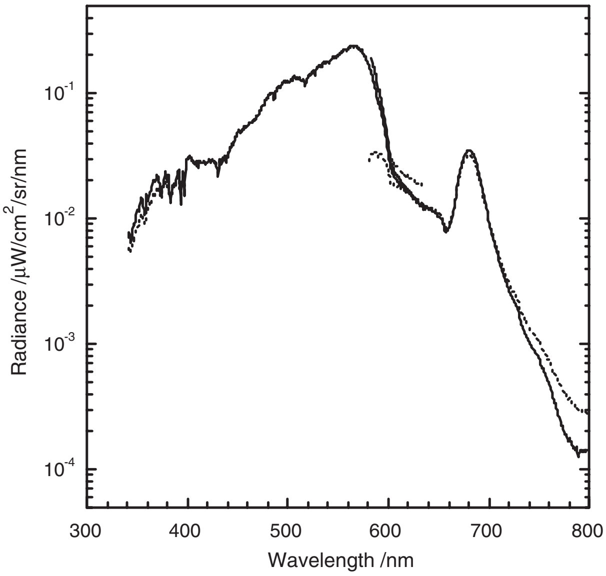

Figure 5. Uncorrected (- - - -) and stray-light-corrected (——) up-welling in-water data from Station 13 acquired with the MOS Profiler during MOCE-5 cruise.

4. Summary

Single-grating spectrographs have a small, but finite, amount of scattered light arising from imperfections in the grating and other optical elements in the system. For these instruments, it is important to characterize the instrument for stray light and correct its response, in particular when the calibration source and an unknown (measured) source's spectral distribution differ significantly.

In this work, a general approach was developed to correct spectrographs for stray light. A separate recursion relation describes the correction to a spectrograph's responsivity and subsequent radiance measurements of unknown sources. A dual-spectrograph instrument, the MOS, was characterized on SIRCUS using tunable laser sources and corrected for stray light using equations (6) and (8). One can compare the spectrographs' stray-light-corrected spectral responsivities obtained by measuring a conventional lamp-illuminated integrating sphere source with those obtained using tunable lasers. The good agreement between the two approaches validated the stray-light correction approach. Correcting in-water data sets acquired with the MOS Profiler gave encouraging results, with a significant reduction in the difference in measured up-welling radiance between the two spectrographs in their overlap region.

Acknowledgments

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